



Theoretical Minimum Energies To Produce Steel for Selected Conditions

March 2000

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Prepared under contract to
Energetics, Inc.
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For the
U.S. Department of Energy
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EXECUTIVE SUMMARY

The energy used to produce liquid steel in today's integrated and electric arc furnace (EAF) facilities is significantly higher than the theoretical minimum energy requirements. This study presents the absolute minimum energy required to produce steel from ore and mixtures of scrap and scrap alternatives. Additional cases in which the assumptions are changed to more closely approximate actual operating conditions are also analyzed. The results, summarized in Table E-1, should give insight into the theoretical and practical potentials for reducing steelmaking energy requirements. The energy values have also been converted to carbon dioxide (CO₂) emissions in order to indicate the potential for reduction in emissions of this greenhouse gas (Table E-2).

The study showed that increasing scrap melting has the largest impact on energy consumption. However, scrap should be viewed as having "invested" energy since at one time it was produced by reducing ore. Increasing scrap melting in the BOF may or may not decrease energy if the "invested" energy in scrap is considered.

Table E-1. Comparison of Theoretical Minimum Energy and Actual Energy Requirements for Selected Processes

Process	Energy (GJ/metric ton product)				
	Actual Requirements [10 ⁶ Btu/ton]	Absolute Minimum [10 ⁶ Btu/ton]	% Difference	Practical Minimum [10 ⁶ Btu/ton]	% Difference
Liquid Hot Metal (5%C)	13 - 14 [11.2 - 12.1]	9.8 [8.5]	25 - 30	10.4 [9.0]	20 - 26
Liquid Steel (BOF)	10.5 - 11.5 [9.1 - 9.9]	7.9 [6.8]	25 - 31	8.2 [7.1]	22 - 29
Liquid Steel (EAF)	2.1 - 2.4 [1.8 - 2.1]	1.3 [1.1]	38 - 46	1.6 [1.4]	24 - 33
Hot Rolling Flat	2.0 - 2.4 [1.7 - 2.1]	0.03 [0.03]	99	0.9 [0.8]	55 - 63
Cold Rolling Flat	1.0 - 1.4 [0.9 - 1.2]	0.02 [0.02]	98 - 99	0.02 [0.02]	98 - 99
18-8 Stainless Melting	--	1.2 [1.0]	--	1.5 [1.3]	--

Notes: Actual includes yield losses and is the average of state-of-art and less-efficient operations for the United States, Japan, and Europe. All of the values exclude electrical generation and transmission losses. BOF energy is primarily from hot metal; actual process consumes 0.2 to 0.4 GJ/t and, if CO is oxidized to CO₂, could theoretically produce 0.5 GJ. For 18-8 stainless no estimates are available, in particular for HCFcCr. In all cases, full credit is taken for the energy in off gas.

Table E-2. Comparison of Theoretical Minimum and Actual CO₂ Emissions for Selected Processes

Process	CO ₂ Emissions (kg/metric ton product)				
	Actual Emissions [lbs/ton]	Absolute Minimum [lbs/ton]	% Difference	Practical Minimum [lbs/ton]	% Difference
Liquid Hot Metal	1,447 - 1,559 [2,894 - 3,118]	1,091 [2,182]	25 - 30	1,158 [2,316]	20 - 26
Liquid Steel (BOF)	189 - 207 [378 - 414]	144 [288]	24 - 30	144 [288]	24 - 30
Liquid Steel (EAF)	364 - 416 [728 - 832]	225 [450]	38 - 46 [76 - 92]	277 [554]	24 - 33
Hot Rolling	110 - 132 [220 - 264]	2 [4]	98 [196]	50 [100]	55 - 62
Cold Rolling	173 - 243 [346 - 486]	4 [8]	98 [196]	4 [8]	98
18-8 Stainless Melting	—	208 [416]	--	260 [520]	--

Note: Based on theoretical minimum energy consumption shown in Table E-1.

Other conclusions that can be drawn from the findings are as follows:

- Elimination of ore agglomeration and cokemaking, which are not theoretically necessary to produce steel, would yield significant energy savings.
- Effective utilization of the energy contained in the off gases from the blast furnace, coke plant, and direction reduction process is essential.
- The best scrap substitute with respect to energy usage is liquid pig iron or hot metal.
- Gangue and ash in ore and coal increase minimum ironmaking energy by about 6%.
- In BOF steelmaking, the energy to produce steel is less than the energy to produce iron because scrap is melted in the process.
- Dirt in scrap and air entrainment in an EAF increase the energy required by about 25%.
- When carbon is used in the EAF, about 38% of the CO must be post combusted to CO₂ to equal electrical energy, even taking into account the production and transmission losses associated with electrical energy.
- The melting energy for stainless steel is similar to the melting energy for carbon steel, but is much greater if the energy associated with ferrochrome is included.
- Direct charging of slabs or billets reduces total rolling energy by about 80%.

1. INTRODUCTION

The absolute theoretical minimum energies to produce liquid steel from idealized scrap (100% Fe) and ore (100% Fe_2O_3) are much lower than consumed in practice, as are the theoretical minimum energies to roll the steel into its final shape. ***This study presents the absolute minimum energy required to produce steel from ore and mixtures of scrap and scrap alternatives, clearly defining the necessary assumptions involved. The energy calculations are then repeated for a series of cases in which the assumptions are changed one by one to more closely approximate the actual conditions.***

The results should give insight as to what is theoretically and practically possible in terms of reducing the energy required to produce steel and will also indicate what factors cause significant increases in energy consumption. The theoretical minimum energies will be compared to typical actual energy consumptions to determine the potential energy savings for each process. In addition, the theoretical minimum energies will be converted to CO_2 emissions (detailed in Appendix A), using assumptions as to the type of energy used and national averages for CO_2 for the type of energy used.

It is not the objective of this study to examine *actual* energy consumptions or CO_2 emissions. However, it is useful to compare approximate industry averages to the minimums to see what the potential energy savings are for each process. These comparisons also indicate the relative energy intensities of the different steelmaking processes. Particular attention is given to ironmaking, which consumes 70-80% of the energy in integrated steel production, and the electric furnace, which consumes the largest portion of the overall energy in scrap-based production.

Objectives

- Compute the theoretical energy required in the major steelmaking processes for a number of conditions
- Compare the theoretical minimum energies to typical actual energy consumptions to determine the energy saving potential for each process considered
- Convert the theoretical minimum energies to CO_2 emissions using the national averages for the type of energy used in the process

2. BASIC ASSUMPTIONS AND CASES CONSIDERED

The calculations performed are theoretical; the basic assumptions are given on the next page. The baseline calculations are the absolute minimum energy to produce liquid iron from pure ore and scrap. The theoretical minimum energy is then computed for a series of cases, including

- blast furnace ironmaking,
- direct reduction,
- oxygen steelmaking, and
- electric arc furnace (EAF) steelmaking.

Also calculated is the energy required for production of hot and cold rolled sheet from conventional slab casters (254 mm or 10 inch) and thin slabs (50 mm or 1.97 inch) and for the production of bars

(25.4 mm, or 1 inch) from a billet (10.16 mm sq, or 4 inch sq). A number of specific issues are also addressed, including the energy and CO₂ emissions for calcining limestone, using carbon in EAF, the effect of yield losses, and the effect of air entrainment in the EAF.

Assumptions Used in the Calculations

- Only energy directly used in the process is considered.
- Energy to produce materials such as alloys, oxygen, refractories, and electrodes is excluded.
- Energy loss in producing and transmitting electrical energy is excluded in initial energy calculations. It is considered for CO₂ emissions.
- Energy and heat losses are excluded. For example, heat losses from furnaces and energy losses from mechanical and electrical equipment are not considered.
- Energy credits are allowed but noted. For example, the chemical and thermal energy in the off gas from the blast furnace is credited to the process.
- Energy used in ore agglomeration and cokemaking are excluded; these are treated separately.
- Energy loss due to yield loss is not considered in the theoretical minimum calculations. However, the minimum energy loss resulting from yield losses is discussed in Section 8.

3. METHODOLOGY

Several different types of energy were considered in the calculations of theoretical minimum energy requirements, including

- sensible or heating energy,
- melting and phase transformation energy,
- heats of reactions, and
- heats of solution.

The required thermodynamic data was taken from several sources.⁽¹⁻⁶⁾ Computer programs were developed that incorporated the energy and materials balance for the process being considered. The accuracy of the calculation depends on the accuracy of the data used. In general, the uncertainties of the calculated energies is 1 to 3%.

Sensible or Heating Energy

In all cases considered, input materials such as ore, carbon, oxygen, and scrap must be heated. The heat ΔH is given by:

$$\Delta H = \int_{T_1}^{T_2} C_p dT$$

C_p = Heat capacity which is a function of temperature

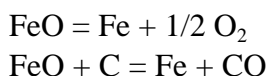
T_1, T_2 = the initial and final temperatures

Melting and Phase Transformation

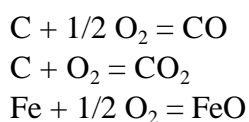
The energies associated with materials melted in the process or going through phase transformations are included.

Heats of Reactions

Chemical reactions either require energy (endothermic) or give off energy (exothermic). An example of an endothermic reaction is the dissociation or reduction by carbon of FeO:



Examples of exothermic reactions are the oxidation of carbon to CO or CO₂ and of iron:



Heats of Solution

When two or more components go into solution, heat can be given off or absorbed. These heats compared to the other types considered are usually small. Examples include the heat of mixing of CaO and SiO₂ and of Fe and carbon.

4. ABSOLUTE THEORETICAL MINIMUM ENERGY VALUES

The absolute theoretical minimum energy values for ore reduction and scrap melting are shown in Table 1 and discussed below.

Ore Reduction

The theoretical minimum energy to produce steel from ore was computed by assuming ore is pure Fe₂O₃ and is reduced at 298 K, with the resulting iron heated to its melting point and melted. Iron goes through a number of phase changes whose energies are included. For the theoretical minimum, no super heat is required and the product is cast into its final shape without finishing. For this case the energy is 8620 MJ/tonne. For moderate super heat to 1873 K the energy is 8673 MJ/tonne.

Scrap Melting

The theoretical minimum in this case is simply heated and melted. The energy is 1,274 MJ/tonne. For super heating to 1873 K the energy increases to 1327 MJ/tonne. As in the previous case, it is assumed the product is cast into its final shape.

**Table 1. Absolute Theoretical Minimum Energy to Produce Steel
from Pure Ore (Fe_2O_3) and Pure Scrap (Fe)**

Raw Material	Absolute Theoretical Minimum Energy as a Function of Tap Temperature (MJ/t)	
	1813 K	1873 K
Ore (Fe_2O_3)	8,620	8,673
Scrap (Fe)	1,274	1,327

5. CASES APPROACHING ACTUAL CONDITIONS

Blast Furnace Ironmaking

Blast furnace ironmaking or any ironmaking process requires more energy and releases more CO_2 than any other process to produce steel. The reduction of Fe_2O_3 to Fe is by far the most energy-intensive step. The theoretical energy requirements to produce liquid hot metal for selected conditions along are presented below, with the specific assumptions. Liquid hot metal or pig iron is defined as iron containing 4% to 5% carbon. Full credit is given for the energy in the off gas. The ironmaking results are summarized in Table 2.

Ironmaking Case I - Absolute minimum. The iron blast furnace does not produce pure iron but rather iron nearly saturated with carbon (typically about 5% C). The tap temperature is usually about 1723 K (1450°C). In this case the energy associated with the carbon is significant and there is a small positive heat of solution. The energy required to produce hot metal for this case is 9,805 MJ. For a tap temperature of 1773 K the energy increases to 9,918 MJ. The energy of carbon associated with the product (50 kg/t) at this point does not release any CO_2 ; the CO_2 is released during steelmaking. Also, the small heat of solution is given back during steelmaking as the carbon is burned.

Ironmaking Case II - Effect of slag resulting from gangue in ore. Ore is not pure Fe_2O_3 but contains gangue or impurities, primarily SiO_2 and Al_2O_3 . An ore with 6% gangue and an assumed consumption of 4% SiO_2 , 1% MnO , and 1% Al_2O_3 was considered. To form a blast furnace slag, lime (CaO) is added. A typical slag will have a basicity (B) of 1.2, where B is defined as

$$B = \frac{(\% \text{CaO})}{(\% \text{SiO}_2)}$$

**Table 2. Minimum Energies to Produce Liquid Hot Metal at 1723 K
(1450°C or 2642°F) for Selected Conditions**

Metal Composition	Gangue	Ash	Energy (MJ/t HM)
Fe - 5%C	No	No	9,805
Fe - 5%C	Yes	No	10,216
Fe - 5%C - 0.5%Si - 0.5%Mn	Yes	No	10,268
Fe - 5%C - 0.5%Si - 0.5%Mn	Yes	Yes	10,421

Notes: Gangue - 4% SiO₂ - 1% Al₂O₃ - 1% MnO of ore
Ash - 5% of 500 kg of coal and coke or 25 kg/t HM

$$\text{Slag Basicity} \left(\frac{\%CaO}{\%SiO_2} \right) = 1.2$$

Energy credit for off gas approximately 5,400 - 5,600 MJ/t HM in each case

In this case all the gangue is assumed to enter the slag. In the calculation, the energy to heat and melt the gangue and CaO are included. There is a significant negative heat of solution or heat release of the slag components. Because of the presence of gangue, the energy increases to 10,216 MJ per tonne of hot metal.

Ironmaking Case III - Effect of slag and reduction of SiO₂ and MnO in slag. During ironmaking some of the SiO₂ and MnO is reduced. A typical metal composition is as follows:

Fe -- 94%
C -- 5%
Si -- 0.5%
Mn -- 0.5%

When the energy for slag formation and reduction of SiO₂ and MnO is included, the energy is 10,268 MJ per tonne of hot metal for a tap temperature of 1773 K.

Ironmaking Case IV - Effect of coke ash. Coke and injected coal contain ash. For this case 500 kg of coke plus coal per tonne of hot metal is assumed, with an average ash content of 5% (the ash is assumed to contain 4% SiO₂, 1% Al₂O₃, and 1% MnO). The assumed 500 kg of coke plus coal/tonne hot metal is *not* the theoretical minimum but reflects typical actual values. The other conditions for slag and reduction are similar to Case III, and the energy increases to 10,421 MJ per tonne of hot metal.

Direct Reduction

The production of direct reduced iron by a number of processes has increased dramatically in the past five years. For the purposes of this report direct reduction is defined as any process that converts ore into a solid product containing primarily metallic iron. The product will also contain gangue from the ore, along with reductant, carbon, and unreduced iron oxide (FeO). In most cases, natural gas (CH₄) supplies the energy. Examples of such processes are Midrex, HyL, FINMET, CIRCORED, and Iron Carbide.

The general assumptions for direct reduction are the same as for ironmaking in a blast furnace. The gangue is assumed to be entirely SiO₂. It is also assumed that the ore is heated to 900°C and reduced. Full credit for the energy in the off gas is taken. In these processes the off gas is usually recycled back into the process, and the chemical energy is used but some thermal energy is lost.

As in the reduction of liquid hot metal, the simplest case is considered first and then realistic computations such as gangue in the ore and carbon in the product are added. All energy values given are per tonne of product. Some products require more energy when used to produce liquid steel in an EAF, which is discussed in a later section of this report. The results of the five cases considered are given in Table 3.

Table 3. Minimum Energies to Produce Direct Reduced Iron at 1173 K (900°C or 1620°F) Reduction Temperature for Selected Conditions

Ore	Product	Energy (MJ/tonne)
Pure Fe ₂ O ₃	Fe	8,360
Fe ₂ O ₃ - 1.4% SiO ₂	Fe - 2% SiO ₂	8,380
Fe ₂ O ₃ - 1.4% SiO ₂	Fe - 2% SiO ₂ - 8% FeO	7,900
Fe ₂ O ₃ - 1.5% SiO ₂	Fe - 2% SiO ₂ - 8% FeO - 2% C	8,427
Fe ₂ O ₃ - 1.5% SiO ₂	Fe - 2% SiO ₂ - 7.7% FeO - 6% C	9,432

Note: Full credit is assumed for off gas

It is important to note that the energy per tonne of iron is different in each case and the energy to melt the materials varies. Later in this section, the total energy to produce steel is given for a 50% scrap - 50% DRI charge.

Oxygen Steelmaking

Oxygen steelmaking (OSM) does not in itself consume energy but instead generates it. In the process, the carbon, silicon, and other elements in the hot metal are oxidized, producing energy

primarily used to melt scrap. The energy can also be used to melt and smelt (reduce) waste oxide briquettes or smelt ore. The amounts of these oxide-containing materials that can be used are significantly less than scrap because of the energy required to reduce the iron oxides. In the United States scrap is almost exclusively used as a coolant and is included in this analysis.

Table 4 lists the amounts of scrap that can be melted per tonne of hot metal of selected compositions. Also given is the amount of liquid steel produced and the energy per tonne of liquid steel, computed by dividing the energy required to produce the hot metal by the amount of steel produced.

Table 4. Energy to Produce Steel from Hot Metal and Scrap for Selected Conditions

Hot Metal	Slag	Tap T _p (K)	Scrap (kg/t HM)	Steel (kg/t HM)	Energy (MJ/t steel)
Fe - 5% C	--	1873	290	1,240	7,907
Fe - 5% C	--	1923	244	1,194	8,212
Fe - 5% C - 0.5% Si (coke ash)	B=3 30% FeO	1873	401	1,328	7,853
Fe - 5% C - 0.5% Si (coke ash)	B=3 30% FeO	1923	353	1,278	8,154
Fe - 5% C - 0.5% Si (coke ash)	B=3 20% FeO	1873	389	1,320	7,894
Fe - 5% C - 0.5% Si (coke ash)	B=3 20% FeO	1923	341	1,270	8,205

Note: The decrease in energy per tonne of steel for oxidizing Si and Fe is due to increased scrap melting.

The calculations assume CO to be the off gas no post combustion. For 5% C in the hot metal the potential energy in the off gas ranges from 950 MJ/t (steel) to 1,000 MJ/t if the CO is oxidized to CO₂.

The results in Table 4 indicate that less energy per tonne of steel is obtained when silicon is present in the hot metal and iron is oxidized. This is somewhat misleading because the reduced energy per tonne of steel is from melting scrap using the additional energy from the oxidation of Si and Fe. Since it takes considerably more energy to produce hot metal from ore than to melt scrap, the energy per tonne of steel produced is reduced when melting more scrap in OSM. This important fact can be illustrated by considering a case in which the additional scrap melted by oxidizing Si and Fe was simply melted in another process. For the case when there is no silicon or iron oxidized to the slag, 290 kg of scrap is melted and the energy per tonne of steel is 7,907 MJ while for 30% FeO and 0.5% Si, 401 kg of scrap is melted and the energy is 7,853 MJ per tonne of steel. If the additional 111 kg of scrap was simply

melted separately, it would require 146 MJ. This reduces the average energy per tonne of steel to 7,200 MJ for no FeO or SiO₂ in the slag if the additional 111 kg of scrap was simply melted.

Electric Furnace Steelmaking with Scrap

A number of cases were considered for scrap and scrap alternative melting in an EAF. The results for 100% scrap melting are summarized in Table 5. The energy loss in producing electricity or the energy required to process the scrap is not considered. Only the energy consumed in the process is included, not the energy to produce other materials, such as electrodes and refractories.

Table 5. Theoretical Minimum Energies to Produce Steel from Scrap for Selected Conditions, Tap Temperature 1873 K (1600°C or 2912°F)

Scrap	Slag	Energy (MJ/t)
Fe	--	1,327
Fe - 0.1%C - 0.2%Si	B = 2.5 %FeO = 25%	1,289
Fe - 0.1%C - 0.2%Si 1% dirt	B = 2.5 %FeO = 25%	1,352
Fe - 0.1%C - 0.2% Si 1% dirt	B = 2.5 %FeO = 35%	1,325
Fe - 0.1%C - 0.2%Si 1% dirt 100 Nm ³ air entrainment	B = 2.5 %FeO = 25%	1,577

Note: The decrease in melting energy with FeO in slag is due to oxidation of Fe

EAF Case I - Absolute Minimum to Melt Iron. The absolute minimum energy is 1,327 MJ/t, the amount of energy required to heat and melt scrap and super heat the metal to 1873 K.

EAF Case II - Scrap Containing 0.1%C - 0.2%Si. In this case, it is assumed that the carbon remains in the steel and the silicon is oxidized to SiO₂. Flux (CaO) is also heated and melted, yielding a slag with a basicity of 2.5 and 25% FeO. The energy requirement is 1,289 MJ/t. The reduction in energy from Case I is due to the oxidation of Si and Fe to the slag, which results in a yield loss of 0.6%.

EAF Case III - Scrap Containing 0.1%C - 0.2%Si + 1.0% (10 kg) "Dirt." Scrap also has other materials with it such as water, soil or dirt, and oil. Based on the final slag formed, considerable amounts of materials containing SiO₂ and Al₂O₃ (e.g., dirt) enter the furnace.

For 10 kg per tonne of scrap of SiO_2 plus Al_2O_3 and maintaining a slag basicity of 2.5, the energy required is increased to 1,352 MJ/t, with a yield loss to the slag of 2.5%

EAF Case IV - Air Entrainment. During EAF steelmaking large quantities of air can be entrained into the furnace through the furnace door and other openings. It is estimated that 100 nm^3 /tonne of air can be entrained. If the N_2 leaves at 1473 K or 1873 K, the heat associated is 165 MJ and 225 MJ, respectively, increasing the energy from Case III to 1,517 MJ and 1,577 MJ/t, respectively.

Electric Furnace Steelmaking with DRI and Scrap

The energy required to produce steel with 50% scrap and 50% scrap substitute was calculated. The scrap was assumed to contain 0.2% Si and 10 kg dirt per tonne. There is no post combustion or air entrainment in the process. The slag is assumed to have basicity of 2.5 and 25% FeO. The energy required to produce steel (0.05%C) for several cases is given in Table 6. This table also shows the energy required to produce steel with solid and liquid pig iron as 50% of the charge. The total energy given in Table 6 includes the energy to produce the DRI (shown in Table 3).

There are numerous other combinations of scrap and DRI and other assumptions with regards to slag and post combustion, which were covered in the AD Little report to AISI⁽⁷⁾.

6. PRODUCTION OF STAINLESS STEEL

There are numerous grades of stainless steel produced in the United States. The most common is 18-8 type stainless, which contains 18% Cr and 8% Ni. This analysis assumes the production of a generic 18-8 type stainless steel in an EAF-AOD (Argon Oxygen Decarburization) sequence, which accounts for over 90% of U.S. stainless steel production.

In the EAF, a mixture of stainless steel scrap, steel scrap, high carbon ferrochrome (HCFeCr), and nickel are melted and the carbon content is reduced to about 1%. The metal is then transferred to an AOD vessel where a mixture of O_2 - Ar or O_2 - N_2 gases oxidizes the carbon to its desired level. The AOD itself does not theoretically require energy and is therefore not considered. After the AOD, a reductant containing either silicon or aluminum is added to the slag to recover chromium, which is oxidized to slag. For the assumptions of the present study, this stage also need not be considered.

A typical charge to the EAF per tonne of steel is as follows:

Steel Scrap	--	350 kg
Stainless Scrap	--	400 kg

The carbon is combusted with oxygen down to 1.0%. The absolute minimum energy for melting the above charge is 1,213 MJ, which is less than melting Fe because of carbon oxidation. If the scrap contains 1% dirt and there is no air entrainment, the melting energy is 1,275 MJ/t.

Table 6. Theoretical Minimum Energies to Produce Liquid Steel at 1873 K (1600°C or 2912°F) from 50% Scrap and 50% Scrap Substitute

Scrap Substitute	Melting Energy (MJ/t)	Charge Energy (MJ/t)	Total Energy (MJ/t)
None (100% Scrap Case)	1,289	--	1,289
Fe - 2% SiO ₂	1,403	4,296	5,698
Fe - 2%SiO ₂ - 8%FeO	1,559	4,233	5,792
Fe - 2%SiO ₂ - 8%FeO - 2%C	1,483	4,565	6,048
Fe - 2%SiO ₂ - 7.7%FeO - 6%C	1,328	5,223	6,551
Liquid Pig Iron	487	5,388	5,875
Solid Pig Iron	1,145	5,388	6,533

Notes: Liquid Pig (Hot Metal) charged at 1723 K, all others 298 K
 If air entrainment is included, it will add 238 MJ/t in each
 Slag has B = 2.5 and 25% FeO

HCFeCr	--	250 kg
Nickel	--	48 kg

According to the initial assumptions and boundaries of the present calculations the energy to produce the high carbon ferrochrome is not included. The amount of alloys for carbon steel production is much smaller than it is for stainless steel. Since the energy in ferrochrome is so high, it is useful to estimate the theoretical minimum for its production. Only the very simplest case of the absolute minimum for the production of HCFeCr is considered.

HCFeCr is produced from chromite ore whose composition depends on the specific mine location. The major component is FeCr₂O₄. For the absolute minimum, the ore is considered to be pure FeCr₂O₄ and the product 61% Cr - 33% Fe - 6% C. The absolute minimum energy is 11.7 GJ/tonne of product. For the 250 kg used in the present example, the absolute minimum is 2,925 MJ per tonne of steel; the actual energy will be over 4,000 MJ. It should be noted that HCFeCr is not produced domestically and therefore no energy is used in the United States. If the minimum energy to produce ferrochrome is included, the total energy is increased to 3,200 MJ/tonne of 18-8 stainless steel.

7. ROLLING

There are two general types of rolling -- hot and cold. With hot rolling, the steel either is reheated or directly charged after casting. Reheating is the major energy consumer in the rolling process. For both hot and cold rolling, energy is also consumed in deformation, where the deformation energy (E) is given by

$$E = s \epsilon c$$

where

σ = the yield stress

ϵ = strain or deformation

c = a constant describing the shape of the stress strain curve, assumed to be an average of 0.7

The strain is defined in terms of the initial and final dimensions, t_o and t_f , respectively.

$$\epsilon = \ln \frac{t_o}{t_f}$$

The yield strengths used in the following calculations were taken from the *Making, Shaping and Treating of Steel*.⁽⁸⁾

Cases included were hot and cold rolling for flat rolled carbon steel and 18-8 type stainless (starting from both normal slabs and thin slabs), as well as hot rolling of bars from billet. The effects of direct charging and billet splitting are also included in the analysis.

For hot rolling, the deformation energy is low because the yield stress is low at high temperatures. For stainless steel, the yield stress is about three times higher than for carbon steel, while for bars it is slightly higher than for flat steel because the carbon content is generally higher. The energy used for heating is fossil fuel and for rolling electrical. Table 7 lists the minimum energies for rolling, assuming no energy or yield losses.

The results in Table 7 indicate that reheating the slab or billet accounts for the vast majority of the rolling energy. If slabs of normal thickness are directly charged, as is the case for most thin slabs, the energy for rolling these slabs is similar to that for thin slabs. Strip casting a 2-mm strip does not significantly reduce the total energy if the normal slab is directly charged. The total energy for a thin slab with hot and cold rolling with direct charging is 33 MJ, compared to cold rolling a 2-mm strip to 1 mm, which requires 17 MJ.

During hot rolling the metal being processed cools and must be reheated or deformed at a lower temperature. These effects require more energy but are not considered.

Table 7. Theoretical Minimum Energies to Roll Steel for Selected Products and Conditions

Rolling Type	Rolling Temperature (K)	Slab Temperature ^a (K)	Reduction (mm)	Energy (MJ/t)		
				Heat	Deformation	Total
Flat Carbon Slab (25.4 cm or 10 inch)						
Hot	1473	298	254 to 2	825	25	850
Hot	1473	1173	254 to 2	270	25	295
Hot	1473	1473	254 to 2	--	25	25
Cold	298	298	2 to 1	--	17	17
Flat Carbon Slab (5.0 cm or 1.97 inch)						
Hot	1473	298	50 to 2	825	16	841
Hot	1473	1173	50 to 2	270	16	286
Hot	1473	1473	50 to 2	--	15	16
Cold	298	298	2 to 1	--	17	17
Flat 18-8 Stainless Steel Slab (25.4 cm or 10 inch)						
Hot	1473	298	254 to 2	825	72	897
Hot	1473	1173	254 to 2	271	72	342
Hot	1473	1473	254 to 2	--	72	72
Cold	298	298	2 to 1	--	51	51
Bar Carbon (10 cm billet to 2 cm bar)						
Hot	1473	298	10 sq to 2 sq	825	20	845
Hot	1473	1473	10 sq to 2 sq	--	20	20
Hot	1473	1173	10 sq to 2 sq	270	20	290
Hot ^b	1473	1473	10 sq to 2 sq	--	11	11

a Slab temperature prior to rolling

b Billet split into 4 pieces prior to rolling

8. EFFECT OF YIELD LOSSES ON ENERGY

The calculation of minimum energies assumed no process yield losses. However, yield losses occur in all processes, and their effect on energy depends on where the yield loss occurs and how much energy is "invested" in the iron or steel to that point. Some forms of yield loss have been taken into account and the energy reclaimed in the calculation. For example, in steelmaking Fe is oxidized to the slag, releasing energy that is used in the process. This energy release has been included in the steelmaking energy calculation. For oxygen steelmaking, this added energy increased the hot metal requirement and, therefore, the energy per tonne of steel. For scrap-based EAF, the "invested energy" in the scrap was not included.

The following section addresses the impact of yield losses related to the various processes. In all cases, the energy invested in the product is assumed to be that for the most likely case for production. For example, for oxygen steelmaking the most likely case for production is the case for hot metal containing silicon. The most likely case for production in the EAF is assumed to include slag and air entrainment. A summary of the effect of yield loss on the minimum theoretical energy requirements to produce steel is summarized in Table 8.

Ironmaking and Hot Metal Treatment

Significant yield losses can occur during tapping, handling, and treatment of hot metal. In particular, iron is extracted with the slag during slag removal after hot metal desulfurization. Yield losses of 1% to 3% are typical; for a 1% yield loss of liquid pig iron the energy loss would be 104 MJ. If the iron is recovered from the slag and reused, only the sensible and melting energy (about 14 MJ) is lost.

Steelmaking

Yield losses in both oxygen steelmaking and EAF steelmaking can be significant. The highest yield loss is FeO to the slag, which can be 5% to 10%. This yield loss releases energy, which was considered, but more iron must be charged. Both of these effects were taken into account in the results given for OSM and the EAF. However, there is no energy charge for the increased scrap usage. Other yield losses can be vaporization of iron (which is oxidized to the dust), other iron losses to the dust, and losses during tapping and handling.

Vaporization of iron consumes a considerable amount of energy in steelmaking. The energy is not recovered when the vaporized iron is oxidized in the off gas. For 1.0% iron vaporizing in the BOF and no energy recovery from iron oxidation, the energy loss is the energy invested in the steel (80 MJ) and the heat of vaporization (64 MJ), or a total of 144 MJ/t of steel. Typical losses by vaporization are about 0.5% to 1.0%. In the case of 1.0% iron vaporizing in the EAF, the invested energy in the steel is less (13 MJ) and the total energy loss is 77 MJ.

The direct energy lost by vaporization, 64 MJ, can actually cause a larger decrease in energy for oxygen steelmaking. The energy loss will result in less scrap melting, which will cause a shift from scrap to hot metal. Since hot metal requires considerably more energy than melting scrap, the resulting increase in energy could be as high as 500 MJ.

Iron is also lost to the dust by simple metal ejection. In this case, only the energy invested is lost. Again, the iron is oxidized in the off gas and little is recovered. For a 1.0% yield

Table 8. Effect of Yield Loss on Minimum Theoretical Energies to Produce Steel for 1% Yield Loss

Process	Type of Loss	Energy (MJ/t)
Hot metal loss in pretreatment	Hot metal loss to slag but recovered	14
Hot metal loss in pretreatment	Hot metal loss to slag not recovered	104
Direct Reduction	Fines lost	60
Direct Reduction	Fines recycled	6
BOF	Fe vaporized to dust	144
EAF	Fe vaporized to dust	102
BOF	Fe ejected to dust	80
EAF	Fe ejected to dust	16
Hot rolling	Fe lost but recovered	13
Cold rolling	Fe lost after reheating for	34

Notes: Losses to slag in BOF and EAF were accounted for in the process.

For rolling, if the metal is not recovered or oxidized, the energy invested in the steel is lost (about 80 MJ for BOF and 16 MJ for EAF).

The energy consumed by Fe vaporization reduces scrap melting, thus requiring more hot metal per tonne of steel. This could represent 500 MJ due to the higher energy associated with hot metal.

loss by metal ejected, the energy loss is 80 MJ for OSM and 16 MJ for EAF steelmaking. The vaporization or loss of other metals, such as zinc, are possible but not considered.

Direct Reduction

Some material is lost as fines during the production of DRI/HBI. This material is often recovered and used to form briquettes or injected into an EAF, in which case there is no energy loss. However, if the material is lost or more likely recycled back into the direct reduction furnace, some energy is lost. Assuming the material does not reoxidize and is recycled into the process, the energy loss is 6.2 MJ/t for 1% material recycle. If the material is reoxidized, the energy loss per 1% is 84 MJ/t.

Rolling

One of the largest cost and energy consumers in rolling is yield loss. The yield loss is usually remelted, requiring about 13 MJ/t for a 1% loss of Fe. However, the yield loss often occurs later in the process when additional energy has been invested into the steel. For example, if the slab is reheated and hot rolled, the yield loss after cold rolling results in a 34 MJ/t loss. If the iron is oxidized or not recovered, the invested energy in the steel is lost. A 1% yield loss applied to the most likely production cases represents an additional loss of 80 MJ/t for BOF steel and 16 MJ/t for EAF steel.

9. OTHER MAJOR ENERGY-CONSUMING ACTIVITIES

Several significant sources of energy consumption were neglected in computing the theoretical minimum energies to produce steel for selected conditions. In some cases, estimates of the energy for these sources can be made while for others the conditions vary greatly and reasonable estimates are difficult.

In theory, ore agglomeration and cokemaking are not necessary for integrated steel production and were not considered. However, these processes are virtually always part of actual integrated steelmaking. Ore agglomeration consists of taking ore fines or concentrate and sintering them into sinter or pellets. Cokemaking is achieved by heating coal under pressure, driving off volatiles and increasing the strength of the material. The theoretical minimum energies for these processes were determined by calculating the energy to heat idealized coal and ore to 1100°C and 1350°C, respectively. In cokemaking the heat of devolatilization is also required but is usually accounted for in computing the energy value of coal. The coke output was taken as 0.768 per tonne of the coal input. The volatiles represent the remainder, which is used as a fuel or for chemicals. The approximate minimum energies for these processes, along with typical actual consumptions, are given in Table 9. The actual energies are given as a range because the values vary according to the actual process and its efficiency.

During cokemaking the volatiles are either used for producing chemicals with energy values and credits or as a fuel in the process itself. The process also produces a relatively rich off gas for which an energy credit is taken. The total credits are about 4.0 to 5.0 GJ/t steel or 11.8 to 14.5 GJ/t coke. The values given in Table 9 have taken into account all the energy credits.

The actual and theoretical minimum energy requirements for ore agglomeration are reasonably close because of the simplicity of the process. For cokemaking the differences are greater because of process complications and yield losses.

There are other energy-consuming process steps or materials used in steelmaking that were beyond the scope of this study. Often the energy consumption is very site-specific; the energy is consumed in another area or even country and depends on process details. These other steps include

- mining of ore, coal, and limestone (integrated production),
- scrap preparation (in scrap-based production),
- transportation of materials to and within the plant, and
- production of alloys, refractories, electrodes, special fluxes, and other materials consumed in steelmaking.

**Table 9. Theoretical Minimum and Typical Energy Consumption
in Cokemaking and Ore Agglomeration**

Process	Theoretical Energy		Actual Energy	
	GJ/t (output)	GJ/t (steel)	GJ/t(output)	GJ/t (steel)
Cokemaking	2.0	0.8	5.4 - 6.2	2.2 - 2.6
Ore Agglomeration	1.2	1.6	1.5 - 1.7	2.1 - 2.4

Note: For cokemaking, full credit is taken for off gas and by-product energy, approximately 4-6 GJ.

10. TOTAL THEORETICAL MINIMUM ENERGY TO PRODUCE STEEL

It is difficult to adequately describe the total energy to produce final steel products because it depends on the process used (EAF or integrated), the raw or charge materials, and the conditions of rolling. Furthermore, the total does not give any insight as to where and how energy can be conserved. However, it is somewhat useful to compare process routes and theoretical to actual energy consumption requirements.

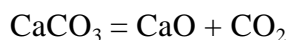
Table 10 summarizes the total energy requirements for producing selected steel products for selected conditions. The most realistic minimum values are about 8,150 MJ/tonne for integrated production and 1,600 MJ/tonne for scrap-based production. Yield losses and other additional losses are not considered.

11. SPECIAL CONSIDERATIONS

This section discusses information regarding theoretical minimum energies that is beyond the primary scope of this report. Whereas the process primarily uses lime (CaO), the raw material is limestone (CaCO₃). The conversion of limestone to lime requires energy and produces CO₂. The impact of SiO₂ on gangue materials in the ore and coke on energy is followed through the process. The impact of post combustion and carbon in the BOF and EAF are also considered.

Energy and CO₂ in Producing CaO

The major flux used in iron and steelmaking is CaO. CaO is obtained from limestone (CaCO₃) by heating it and driving off the CO₂ according to the following reaction:



The reaction will only occur when the equilibrium pressure reaches one atmosphere. Therefore, the reactants must be heated to 1155 K and the energy of the reaction supplied.

**Table 10. Total Theoretical Minimum Energies to Produce
Selected Products for Selected Conditions**

Process	Product	Rolling	Energy (MJ/t)
BF-BOF (Conventional Slab)	Hot Rolled Sheet	Direct Reheat	7,878 8,703
BF-BOF (Conventional Slab)	Cold Rolled Sheet	Direct Reheat	7,895 8,720
EAF (Scrap) (Thin Slab)	Hot Rolled Sheet	Direct Reheat	1,341 2,166
EAF Scrap (Thin Slab)	Cold Rolled Sheet	Direct Reheat	1,358 2,183
EAF (50% DRI) (Thin Slab)	Cold Rolled Sheet	Direct Reheat	6,081 6,906
EAF (Scrap) (Billet)	Bar	Direct Reheat	1,345 2,170
EAF (50% DRI) Billet	Bar	Direct Reheat	6,068 6,893
EAF-AOD Slab	Cold Rolled 18-8 Stainless	Direct Reheat	1,397 2,223
EAF-AOD-(HCFeCr) Slab	Cold Rolled 18-8 Stainless	Direct Reheat	4,323 5,148

Notes: Does not include ore preparation, cokemaking, or yield losses.
 Stainless for melting only and for production of required HCFeCr.
 Liquid steel energy:
 BF-BOF 7853 MJ/t
 EAF-scrap 1355 MJ/t
 EAF-DRI 6048 MJ/t
 EAF-AOD 1275 MJ/t
 EAF-AOD-HCFeCr 4200 MJ/t

To produce one tonne of CaO from CaCO₃ requires a theoretical minimum energy of 4,670 MJ. The product is CaO and CO₂ at 1155 K. It is theoretically possible but highly impractical to utilize the heat contained in the CaO (1,471 MJ). In addition to the energy required, 0.79 tonnes of CO₂ is released per tonne of CaO.

Effect of SiO₂

Silica enters the steelmaking process primarily as gangue in the ore or coke ash. Silicon is also present in scrap. The silica requires energy in ironmaking and steelmaking because it must be heated and melted along with the appropriate amount of lime. The energy in ironmaking increases by about 110 MJ for 1% extra silica in the gangue or ash. However, this SiO₂ requires CaO. Whereas the heating and melting is included in the 110 MJ, the production of the CaO is not for a slag basicity of 1.2, which requires 12 kg CaO per 1% SiO₂. This requires an additional 5.5 MJ, and 0.008 tonnes of CO₂ is released from the limestone.

Energy Credits in Off Gases

Full energy credit was taken for the off gas for the processes of blast furnace ironmaking, cokemaking, and direct reduction. These credits are a large percentage of the total energy. This energy must be efficiently utilized for the processes to be energy-efficient. The off gases can be used in the process itself such as in blast furnace air preheating stoves, in reheating furnaces, or producing steam for electricity. For integrated steel production, including cokemaking, the total energy in off gases can be as high as 6-10 GJ per tonne of steel. Therefore, the efficient use of this energy is critical.

Carbon in Steelmaking

Carbon is usually used as a fuel in the EAF and is sometimes used to melt more scrap in a BOF. The carbon used in an EAF usually contains ash, which reduces its energy value by 5% to 15%, depending on the amount. For these theoretical calculations the material is assumed to be pure carbon. The reaction product in the presence of carbon or iron is primarily CO. If the carbon is only oxidized to CO, it is much less efficient than using the same carbon to produce electrical energy. For the carbon to be as effective as electricity generation and transmission with an efficiency of 36% (which corresponds to 10 MJ/kWh), it must be post combusted (PC) to 37.6% with 100% of the energy going to the steel. The equation below represents the post-combustion percentage:

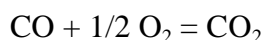
$$PC = \frac{CQ}{CO + CQ_2} \quad (100)$$

These conditions are difficult to achieve in practice, and in the actual case the required PC would be higher because of the ash in the carbon. Therefore, using carbon does not reduce energy use in the EAF, even if the inefficiency of electric power production is considered. However, carbon oxidation does improve productivity and refining of the steel, which is its primary purpose.

Post Combustion

In steelmaking processes, the equilibrium product for the oxidation of carbon is primarily CO, with less than 10% CO₂. It has been recognized for decades that significant quantities of energy are available if the CO can be combusted to CO₂ in such a way that the CO₂ does not react with iron or carbon, and the energy can be transferred to the system.

The post combustion reaction is



After accounting for the heating of the oxygen, the heat released at 1873 K is 255 KJ per mole of CO. For example, if 10% of the CO can be post combusted in OSM with 100% heat- transfer efficiency, the energy released is 106 MJ per tonne of hot metal. This energy can melt 80 kg of scrap per tonne of metal, which can significantly reduce the energy to produce steel because of the shift from ore to scrap. For OSM with a slag basicity of 3 and 30% FeO and a tap temperature of 1873 K, the energy per tonne of steel is reduced from 7,853 MJ to 7,401 MJ. The major reason for the energy savings is the use of more scrap.

In the EAF, large amounts of charge carbon are initially oxidized to CO. About 16 MJ/t of energy is released for 10 kg carbon for each 10% post combustion to CO₂ with 100% heat transfer.

12. COMPARISON OF TYPICAL ACTUAL AND THEORETICAL MINIMUM ENERGY

Table 11 shows the theoretical minimum energy for the most realistic case and the typical range of actual energy consumption for selected processes. The low value for the actual consumptions represents the lowest values for any country as reported by the International Iron and Steel Institute (IISI), not necessarily best practice.⁽⁹⁾ For BOF steelmaking, the energies represent the energy of the hot metal; the steelmaking process itself does not consume significant energy. For hot rolling, the energy values represent a mixture of direct charging and reheating of conventional slabs. Most likely the majority of the slabs are reheated and the theoretical values include reheating.

The results indicate that for ironmaking the absolute maximum energy savings available are about 20% to 25%. Similarly for EAF steelmaking, the absolute maximum savings are about 23% to 33%.

The potential energy savings for rolling are lower simply because the processes use less energy. Although it is not clear from Table 11, the potential for the greatest energy savings in finishing lies in direct charging of slabs and billets. This would require major equipment changes and improved clean steel practices in order to avoid inspection and grinding of slabs and billets.

Table 8 showed the total energy in cokemaking and ore agglomeration to be about 5 GJ/t (steel). If an ironmaking process can be developed that uses coal and ore fines or concentrates, this energy could be eliminated.

Table 11. Practical Theoretical Minimum and Energy for Selected Processes

Process	Energy (GJ/t product)		
	Absolute Minimum	Practical Minimum	Reported Consumption
Liquid Hot Metal (5%C)	9.8	10.4	13 - 14
Liquid Steel (BOF)	7.9	8.2	10.5 - 11.5
Liquid Steel (EAF)	1.3	1.6	2.1 - 2.4
Hot Rolling Flat	0.03	0.9	2.0 - 2.4
Cold Rolling Flat	0.02	0.02	1.0 - 1.4
18-8 Stainless Melting	1.2	1.5	--

Notes: Actual includes yield losses and is the average of state-of-art and less-efficient operations for the United States, Japan, and Europe.

BOF energy is primarily from hot metal; actual process consumes 0.2 to 0.4 GJ/t and, if CO is oxidized to CO₂, could theoretically produce 0.5 GJ.

For 18-8 stainless no estimates are available, in particular for HCFcCr

In all cases, full credit is taken for the energy in off gas.

13. SUMMARY AND CONCLUSIONS

The theoretical minimum energies to produce several steel products for ore- and scrap-based processes were computed. In general, only the energy for the process itself was considered and not the energy used to produce input materials or electricity. The cases included ironmaking, direct reduction, oxygen steelmaking, scrap and scrap substitute, EAF steelmaking, production of 18-8 type stainless, and rolling of cast material to final shape. In addition, the effects of yield loss, gangue, and use of carbon post combustion (as well as other special cases) on energy consumption were estimated. Table 12 presents a comparison of the theoretical minimums to actual typical energy consumption values. Some additional findings are shown in the summary box.

Increasing scrap melting has the largest impact on energy consumption. However, scrap should be viewed as having "invested" energy since at one time it was produced by reducing ore. Therefore, it should be used wisely. For example, oxidizing it to the slag may reduce energy in the process but the "invested" energy is lost. Also, increasing scrap melting in the BOF may or may not decrease energy if the "invested" energy in scrap is considered. Scrap supplies are not unlimited, and new iron from ore will always be required.

Table 12. Comparison of Theoretical Minimum Energy and Actual Energy Requirements for Selected Processes

Process	Energy (GJ/t product)				
	Actual Energy Requirements	Absolute Minimum	% Difference	Practical Minimum	% Difference
Liquid Hot Metal (5% C)	13 - 14	9.8	25 - 30	10.4	20 - 26
Liquid Steel (BOF)	10.5 - 11.5	7.9	25 - 31	8.2	22 - 29
Liquid Steel (EAF)	2.1 - 2.4	1.3	38 - 46	1.6	24 - 33
Hot Rolling Flat	2.0 - 2.4	0.03	99	0.9	55 - 63
Cold Rolling Flat	1.0 - 1.4	0.02	98 - 99	0.02	98 - 99
18-8 Stainless Melting	--	1.2	--	1.5	--

Notes: Actual includes yield losses and is the average of state-of-art and less-efficient operations for the United States, Japan, and Europe.

BOF energy is primarily from hot metal; actual process consumes 0.2 to 0.4 GJ/t and, if CO is oxidized to CO₂, could theoretically produce 0.5 GJ.

For 18-8 stainless no estimates are available, in particular for HCFcCr.

In all cases, full credit is taken for the energy in off gas.

Other conclusions that can be drawn from the findings are as follows:

- Elimination of ore agglomeration and cokemaking, which are not theoretically necessary to produce steel, would yield significant energy savings.
- Effective utilization of the energy contained in the off gases from the blast furnace, coke plant, and direction reduction process is essential.
- The best scrap substitute with respect to energy usage is liquid pig iron or hot metal.

Additional Findings

Effect of Gangue and Ash

- Gangue and ash in ore and coal increase minimum energies by 0.6 GJ (about 6%) for ironmaking.

Direct Reduction

- Energy requirements for direct reduction per tonne of iron are similar to those for the blast furnace.

Scrap in the BOF

- In BOF (OSM) steelmaking, the energy to produce steel is less than the energy to produce iron because scrap is melted in the process.
- Due to the "invested" energy in scrap any process that increases scrap melting lowers the total energy because of the substitution of scrap for ore.

Variables in the EAF

- Dirt in scrap and air entrainment in an EAF increase the energy required by 0.3 GJ/t (about 25% of the total energy).
- Total energy increases dramatically when using scrap substitute such as DRI or pig iron with scrap in an EAF. The best scrap substitute with respect to energy usage is liquid pig iron or hot metal.

Stainless Steel

- The melting energy for stainless steel is similar to the melting energy for carbon steel. However, the energy is much greater if the energy associated with ferrochrome is included.

Direct Charging

- Direct charging of slabs or billets reduces total rolling energy by about 80%.

Ore Agglomeration and Cokemaking

- Ore agglomeration and cokemaking, which are not theoretically necessary to produce steel, have significant theoretical minimum energies (1.6 and 0.8 GJ/t steel, respectively) and actual energies (2.2 and 2.4 GJ/t, respectively).

Limestone Calcination

- Calcination of limestone requires 4.7 GJ/t CaO and releases 0.79 tonnes of CO₂.

Post Combustion

- Post combustion can significantly increase scrap melting in the BOF and decrease energy required in the EAF.

Carbon in the EAF

- When carbon is used in the EAF, about 38% of the CO must be post combusted to CO₂ to equal electrical energy, even taking into account the production and transmission losses associated with electrical energy.

Off-Gas Energies

- Off-gas energies from the blast furnace, coke plant, and direct reduction were significant and were credited to the processes. For example, the total energy credit for coke and ironmaking is 6-10 GJ.

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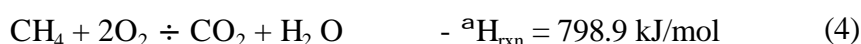
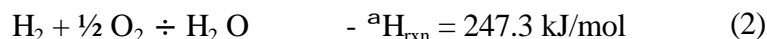
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APPENDIX A

**THEORETICAL CO₂ EMISSIONS
FROM STEELMAKING PROCESSES**

In this section, the CO₂ emissions associated with the energies required to produce steel are calculated. The following tables present theoretical CO₂ emissions from various steelmaking processes for a number of conditions. These conditions are based on those used in the preceding analysis of theoretical energy consumption for steel production.

Emission factors were calculated by considering the heats of reaction for the following reactions:



These reactions represent the basic reactions that occur when fuel (carbon or methane) is combusted. By using these heats of reaction and the energy requirements for each process (shown in the report), the necessary amount of moles of fuel can be calculated. Once the amount of fuel is known, stoichiometry dictates the amount of CO₂ generated by the combustion of that fuel. Because the production of electricity is not a matter of simple chemical reaction, the emission factor for electricity (U.S. grid) accepted by the American Iron and Steel Institute (AISI) was used in this analysis (AISI 1996). Table A-1 shows the emission factors used in this analysis according to the assumptions noted and compares them to the AISI emission factors for each fuel source considered. Some assumptions have been made to simplify calculations and are noted below:

- The energy for ironmaking is assumed to come from 100% carbon and converted entirely to CO₂ when consumed.
- Natural gas is assumed to be 100% methane and converted entirely to CO₂ and H₂O when consumed.
- Electricity emissions include efficiency and transmission losses.
- Emissions for BOF steelmaking are a result of 50 kg C/tonne HM that remains in the liquid pig iron and is used as fuel during oxygen steelmaking. This carbon is not combusted to CO₂ during the ironmaking step and thus is not included in the emissions for ironmaking. Since oxygen steelmaking generates rather than consumes energy, this process has no additional combustion emissions beyond the 50 kg C/tonne HM remaining in the liquid pig iron.

The minimum theoretical energy consumption data presented in the body of this report are not estimates but rather actual physical quantities. When those energy data are converted to CO₂ emissions, a number of assumptions and approximations are necessary. Particularly, while the energy data are simply energy (no fuel type is specified), fuel types must be specified when calculating carbon emissions. Additionally, carbon emission factors have been estimated based on the composition of common fuel sources. The distinction between the theoretical minimum energy consumption as a physical quantity and the minimum CO₂ as an estimate must be made clear.

Table A-1. Emission Factors Used to Convert Theoretical Energy Consumption to CO₂ Emissions

Fuel Source	Theoretical Emission Factor (kg CO₂/MJ)	AISI Emission Factor (kg CO₂/MJ)	Difference (percent)
Coke	0.111	0.109	1.8
Natural Gas	0.055	0.050	9.1
Hydrogen	0	0	0.0
Electricity	N/A	0.173	N/A
Coke Oven Gas	0.055	0.046	16.4

Source: *Survey of Consumption of Energy in the U.S. Iron and Steel Industry*, American Iron and Steel Institute, 1996.

Notes: Coke is assumed to be 100% carbon combusted to 100% CO₂.
Natural gas is assumed to be 100% methane and combusted to 100% CO₂ and H₂O.
Electricity emission factor accounts for transmission and efficiency losses at the power plant (based on IISI value for the U.S. grid).
Hydrogen used as fuel does not result in any CO₂ emissions.
Coke oven gas used as fuel is considered as natural gas when considering CO₂ emissions.

The remainder of this appendix consists of the following tables:

- Table A-2. Absolute Theoretical Minimum CO₂ Emissions for Producing Steel from Pure Ore (Fe₂O₃) and Pure Scrap (Fe)
- Table A-3. Minimum CO₂ Emissions to Produce Liquid Hot Metal at 1723 K for Selected Conditions
- Table A-4. Minimum CO₂ Emissions to Produce Direct Reduced Iron at 1173 K Reduction Temperature for Selected Conditions
- Table A-5. Minimum CO₂ Emissions to Produce Steel from Hot Metal and Scrap for Selected Conditions
- Table A-6. Minimum CO₂ Emissions to Produce Steel from Scrap for Selected Conditions, Tap Temperature = 1873 K
- Table A-7. Minimum CO₂ Emissions to Produce Liquid Steel at 1873 K from 50% Scrap and 50% Scrap Substitute
- Table A-8. Minimum CO₂ Emissions to Roll Steel for Selected Products and Conditions
- Table A-9. Effect of Yield Loss on Minimum CO₂ Emissions to Produce Steel for 1% Loss
- Table A-10. Minimum and Typical CO₂ Emissions in Cokemaking and Ore Agglomeration
- Table A-11. Practical Minimum CO₂ Emissions for Selected Processes

**Table A-2. Absolute Theoretical Minimum CO₂ Emissions
for Producing Steel from Pure Ore (Fe₂O₃) and Pure Scrap (Fe)**

Raw Material	Temperature (degrees K)	Carbon Emissions (kg CO ₂ /tonne)		
		Fuel = Carbon	Fuel = Natural Gas	Fuel = Electricity
Ore (Fe ₂ O ₃)	1813	960	475	1,494
	1873	966	478	1,503
Scrap (Fe)	1813	142	70	221
	1873	148	73	230

Notes: Based on theoretical minimum energy consumption shown in Table 1.
Absolute theoretical minimum energy consumption is independent of fuel type and not based on any actual production process. Therefore, the three main sources of fuel have been used to calculate theoretical carbon emissions for each.

**Table A-3. Minimum CO₂ Emissions to Produce Liquid Hot Metal
at 1723 K for Selected Conditions**

Material Consumption	Gangue	Ash	CO ₂ (kg/ tonne HM)
Fe - 5% C	No	No	908
Fe - 5% C	Yes	No	954
Fe - 5% C - 0.5% Si - 0.5% Mn	Yes	No	960
Fe - 5% C - 0.5% Si - 0.5% MnO	Yes	Yes	977

Notes: Based on theoretical minimum energy consumption shown in Table 2.
Gangue contains 4% SiO₂, 1% Al₂O₃, and 1% MnO. Ash content is 25 kg/tonne hm (5% of coal and coke used).
Fuel used in ironmaking is assumed to be 100% coke.
Carbon that remains in the hot metal (5% C, or 50 kg C/tonne HM) is subtracted from the overall carbon emissions for liquid hot metal production shown in this table. Those carbon emissions are attributed to the process in which that carbon is used as fuel (i.e., raw steel production from hot metal, see Table A-5).

**Table A-4. Minimum CO₂ Emissions to Produce Direct Reduced Iron
at 1173 K Reduction Temperature for Selected Conditions**

Ore	Product	CO ₂ (kg/tonne)
Pure Fe ₂ O ₃	Fe	461
Fe ₂ O ₃ - 1.4% SiO ₂	Fe - 2% SiO ₂	462
Fe ₂ O ₃ - 1.4% SiO ₂	Fe - 2% SiO ₂ - 8% FeO	435
Fe ₂ O ₃ - 1.5% SiO ₂	Fe - 2% SiO ₂ - 8% FeO - 2% C	391
Fe ₂ O ₃ - 1.5% SiO ₂	Fe - 2% SiO ₂ - 7.7% FeO - 6% C	300

Notes: Based on theoretical minimum energy consumption shown in Table 3.
The energy used to produce direct reduced iron is assumed to be 100% natural gas.
When carbon remains in the final product (the final two rows in the table above), that carbon is subtracted from the overall CO₂ emissions of the process. The subtracted CO₂ is attributed to the process in which the carbon is used as fuel (i.e., liquid steel production from scrap and scrap substitute, Table A-7).

**Table A-5. Minimum CO₂ Emissions to Produce Steel
from Hot Metal and Scrap for Selected Conditions**

Hot Metal	Slag	Tap Temp. (K)	Scrap (kg)	Steel (kg/tonne HM)	CO ₂ (kg/tonne)
Fe - 5% C	—	1873	290	1,240	148
Fe - 5% C	—	1923	244	1,194	135
Fe - 5% C - 0.5% Si	B = 3; 30% FeO	1873	401	1,328	138
Fe - 5% C - 0.5% Si	B = 3; 30% FeO	1923	353	1,278	143
Fe - 5% C - 0.5% Si	B = 3; 20% FeO	1873	389	1,320	139
Fe - 5% C - 0.5% Si	B = 3; 20% FeO	1923	341	1,270	144

Notes: Based on theoretical energy consumption shown in Table 4.
Oxygen steelmaking is theoretically an energy-producing process due to the exothermic nature of the reactions taking place. Therefore, fuel consumption is theoretically not needed, and carbon emissions do not result from the combustion of fuels.
The CO₂ emissions shown are the result of the 5% carbon (50 kg/tonne HM) in the hot metal feed that is consumed during steelmaking. The carbon is actually used as a fuel source for melting scrap and is converted to CO₂ in this process.

Table A-6. Minimum CO₂ Emissions to Produce Steel from Scrap for Selected Conditions, Tap Temperature = 1873 K

Scrap	Slag	CO ₂ (kg/tonne steel)
Fe	–	230
Fe - 0.1% C - 0.2% Si	B=2.5; 25% FeO	223
Fe - 0.1% C - 0.2% Si - 1% dirt	B=2.5; 25% FeO	234
Fe - 0.1% C - 0.2% Si - 1% dirt	B=2.5; 35% FeO	230
Fe - 0.1% C - 0.2% Si - 1% dirt - 100 Nm ³ air	B=2.5; 25% FeO	275

Notes: Based on theoretical energy consumption shown in Table 5.
Energy is assumed to be 100% electricity, using a conversion factor of 10,500 Btu/kWh to include transmission and efficiency losses.

Table A-7. Minimum CO₂ Emissions to Produce Liquid Steel at 1873 K from 50% Scrap and 50% Scrap Substitute

Input	Melting Energy (MJ/tonne steel)	Charge Energy (MJ/tonne steel)	CO ₂ (kg/tonne steel)
None (100% Scrap Case)	1,289	–	234
Fe - 2% SiO ₂	1,403	4,296	480
Fe - 2% SiO ₂ - 8% FeO	1,559	4,233	503
Fe - 2% SiO ₂ - 8% FeO - 2% C	1,483	4,565	548
Fe - 2% SiO ₂ - 8% FeO - 6% C	1,328	5,223	640
Liquid Pig Iron	487	5,388	779
Solid Pig Iron	1,145	5,388	893

Notes: Based on theoretical energy consumption shown in Table 6.
Liquid pig iron is charged at 1723 K, all others at 298 K; melting energy is assumed to be 100% electricity.
Charge energy is assumed to be 100% natural gas for DRI and 100% coke for pig iron.
In addition to the CO₂ emissions generated from fuel consumption, the carbon contained in the input materials is converted to CO₂ in this process (10.8 kg C/tonne, 2%C DRI; 33.2 kg C/tonne, 6%C DRI; 25.8 kg C/tonne pig iron).

Table A-8. Minimum CO₂ Emissions to Roll Steel for Selected Products and Conditions

Rolling Temperature (K)	Slab Temperature (K)	Reduction (mm)	Energy (MJ/tonne)		CO ₂ (kg/tonne)
			Heat	Deformation	
Flat Carbon (25.4 cm slab)					
1473	298	254 - 2	825	25	50
1473	1173	254 - 2	270	25	19
1473	1473	254 - 2	–	25	4
298	298	2 - 1	–	17	3
Flat Carbon (5.0 cm slab)					
1473	298	50 - 2	825	16	48
1473	1173	50 - 2	270	16	18
1473	1473	50 - 2	–	16	3
298	298	2 - 1	–	17	3
Flat 18-8 Stainless (25.4 cm slab)					
1473	298	254 - 2	825	72	58
1473	1173	254 - 2	270	72	27
1473	1473	254 - 2	–	72	12
298	298	2 - 1	–	51	9
Bar Carbon (10 cm billet to 2 cm bar)					
1473	298	10 sq - 2 sq	825	20	49
1473	1473	10 sq - 2 sq	–	20	4
1473	1173	10 sq - 2 sq	270	20	18
1473	1473	10 sq - 2 sq	–	11	2

Notes: Based on theoretical energy consumption shown in Table 7.

Heating energy is assumed to be 100% natural gas.

Deformation energy is assumed to be 100% electricity.

**Table A-9. Effect of Yield Loss on Minimum CO₂ Emissions to Produce Steel
for 1% Loss**

Process	Type of Loss	Energy (MJ/tonne)	CO₂ (kg/tonne)
Hot metal loss in pretreatment	Hot metal loss to slag but recovered	14	1.6
	Hot metal loss to slag, not recovered	104	11.6
Direct Reduction	Fines lost	60	3.3
	Fines recycled	6	0.3
BOF	Fe vaporized to dust	144	2.6
	Fe ejected to dust	80	1.4
EAF	Fe vaporized to dust	102	17.7
	Fe ejected to dust	16	2.8
Hot Rolling	Fe lost but recovered	13	2.3
Cold Rolling	Reheating for hot rolling, but recovered	34	5.9

Notes: Based on theoretical energy consumption shown in Table 8.

Energy lost in hot metal loss is assumed to be 100% coke. Energy lost in direct reduction fines is assumed to be 100% natural gas.

Energy lost in EAF and rolling operations is assumed to be 100% electricity.

For BOF steelmaking, emissions are calculated using the average emission rate for the BOF steelmaking calculations (0.018 kg CO₂/tonne/MJ).

**Table A-10. Minimum and Typical CO₂ Emissions
in Cokemaking and Ore Agglomeration**

Process	Theoretical			Actual		
	GJ/tonne output	GJ/tonne steel	CO ₂ (kg/tonne output)	GJ/tonne output	GJ/tonne steel	CO ₂ (kg/tonne output)
Cokemaking	2	0.8	0.11	5.4 - 6.2	2.2 - 2.6	0.30 - 0.34
Ore Agglomeration	1.2	1.6	0.07	1.5 - 1.7	2.1 - 2.4	0.17 - 0.19

Notes: Based on theoretical minimum energy consumption shown in Table 9.
Energy used in cokemaking is assumed to be 100% natural gas.
Energy used in ore agglomeration is assumed to be 100% coke breeze.

**Table A-11. Comparison of Theoretical Minimum and Actual CO₂ Emissions
for Selected Processes**

Process	Absolute Minimum CO ₂ (kg/tonne product)	Practical Minimum CO ₂ (kg/tonne product)	Actual CO ₂ (kg/tonne product)
Liquid Hot Metal	1,091	1,158	1,447 - 1,559
Liquid Steel (BOF)	144	144	189 - 207
Liquid Steel (EAF)	225	277	364 - 416
Hot Rolling	2	50	110 - 132
Cold Rolling	4	4	173 - 243
18-8 Stainless Melting	208	260	—

Notes: Based on theoretical minimum energy consumption shown in Table 11.
Actual includes yield losses and is the average of state-of-the-art and less-efficient operations for the United States, Japan, and Europe.
BOF energy is primarily from hot metal; the actual process consumes 0.2 to 0.4 GJ/tonne. Theoretically if CO is oxidized, it could produce 0.5 GJ/tonne.
For 18-8 stainless melting no estimates of actual emissions were available.

